DOE/NASA CONTRACTOR REPORT

DOE/NASA CR-150510

INDOOR TEST FOR THERMAL PERFORMANCE EVALUATION OF LENOX-HONEYWELL SOLAR COLLECTOR

Prepared by Wyle Laboratories, Solar Energy Systems Division, Huntsville, Ala.

Under sub-contract with

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Federal Systems Division
Huntsville, Alabama 35805

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16. ABSTRACT

This report presents the test procedures used and the test results obtained from an evaluation test program conducted on a Lennox/Honeywell double-covered liquid solar collector under simulated conditions. The Marshall Space Flight Center Solar Simulator was used in accordance with test requirements. The test article is a flat plate solar collector using liquid as the heat transfer medium. The absorber plate is steel with the copper tubes bonded on the upper surface. The plate is coated with black chrome with an absorptivity factor of .95 and emissivity factor of .12. A time constant test and incident angle modifier test were conducted to determine the transient effect and the incident angle effect on the collector.

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William A. Brooksbank, Jr.
Manager
Solar Heating & Cooling Project Office

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1.0 PURPOSE

The purpose of this report is to present the test procedures used and the test results obtained during an evaluation test program. The test program was conducted to obtain thermal performance data on a Lennox/Honeywell double-covered liquid solar collector under simulated conditions. The tests were conducted utilizing the Marshall Space Flight Center Solar Simulator in accordance with the test requirements specified in Reference 2.1 and the procedures contained in Reference 2.2.

2.0 REFERENCES

2.1	ASHRAE 93-P	Method of Testing Solar Collectors Based on Thermal Performance
2.2	MTCP-DC-SHAC-411	Test Procedure For the Evaluation of the Lennox/Honeywell Solar Collector
2.3	MTCP-FA-SHAC-400	Procedure for Operation of the MSFC Solar Simulator Facility

3.0 MANUFACTURER

Honeywell
2600 Ridgway Parkway
Minneapolis, Minnesota 55413

3.1 DESCRIPTION OF TEST SPECIMEN

The test article is a flat plate solar collector using liquid as the heat transfer medium. The absorber plate is steel with the copper tubes bonded on the upper surface. It is coated with black chrome with an absorptivity factor of .95 and emissivity factor of .12. The absorber surface is 15.3 square feet and overall dimensions of the collector are 3'x6'x6 1/2". It has a double glass cover of 1/8" tempered glass and weighs approximately 153 pounds.

4.0 SUMMARY

This test program was conducted to evaluate the thermal performance of a Lennox/Honeywell liquid collector under simulated conditions. The test conditions and thermal performance data obtained during the tests conducted on the simulator are listed in Tables I through IV, respectively. A graphic presentation of the data obtained is also presented in Figure 1. In addition, a time constant test and incident angle modifier test were conducted to determine the transient effect and the incident angle effect on the collector. The results of these tests are presented in Figures 2 through 4 and Tables V and VI.

5.0 TEST CONDITIONS AND TEST EQUIPMENT

5.1 Ambient Conditions

Unless otherwise specified herein, all tests were performed at ambient conditions existing in building 4619 at the time of the tests.

5.2 Instrumentation and Equipment

All test equipment and instrumentation used in the performance of this test program comply with the requirements of MSFC MMI 5300.4 C, Metrology and Calibration. A standard test setup is depicted in Reference 2.3.

Apparatus	Manufacturer/Model	Range and Accuracy
Liquid loop	MSFC Supplied	.1-1.12 GPM
Reference Junction	Pace/150	150 ±1°F
Thermocouple	MSFC Supplied	0-500°F ±1.8°F
Flowmeter	Foxboro/1/2-2 81T361	.1-1.2 ±1% GPM
Resistance Thermometer	Thermal Systems/T200	0-500 ±.05°F
Radiometer	Eppley/8-48	0-400 ±10% BTU/Hr·Ft^2
Directional Anemometer	MSFC Supplied	0-60 MPH
Floor Fans	MSFC Supplied	NA
Solar Simulator	MSFC Supplied	See SHC 3006
Thermopile	Medtherm	0-20°F ±.05°F
Strip Chart Recorder	Mosley 680	NA

6.0 REQUIREMENTS, PROCEDURES AND RESULTS

6.1 Indoor Thermal Performance Evaluation Test

6.1.1 Requirements

The requirements of this test were to obtain performance information at ambient, 100, 120, 150 and 200°F inlet temperatures with a controlled liquid flow rate of 224.9 pounds per hour at solar flux levels of 230 and 270 BTU/Hr·Ft^2 with simulated wind conditions of 0, 10 and 13 MPH. The following data were recorded for the test.

1.	Collector side wall temperature	(°F)
2.	Collector back side temperature	(°F)
3.	Collector outer cover temperature	(°F)
4.	Absorber surface temperature - North side	(°F)
5.	Absorber surface temperature - Center	(°F)
6.	Absorber surface temperature - West side	(°F)
7.	Absorber surface temperature - South side	(°F)
8.	Ambient temperature	(°F)
9.	Liquid inlet temperature	(°F)
10.	Liquid outlet temperature	(°F)
11.	Liquid differential temperature	(°F)
12.	Solar flux	(BTU/Hr·Ft^2)
13.	Flow rate	(Lb/Hr)
14.	Wind speed	(MPH)

Collector temperature measurements were taken from locations identified in Figure 5.

6.1.2 Procedure

This test program was conducted in accordance with detailed procedures contained in Reference 2.2. Briefly stated, these procedures required the following:

1. Prepare test setup; mount collector on test facility and connect instrumentation leads to data acquisition system.

2. Establish required liquid flow rate.

3. Establish required inlet temperature of 100°F.

4. Establish required solar flux level at 230 BTU/Hr·Ft^2.

5. Establish required wind speed of 0 MPH.

6. Record data for 5 minute stabilized period.

7. Repeat above steps as necessary to obtain data under all conditions listed in Table I.

6.0 REQUIREMENTS, PROCEDURES AND RESULTS (Continued)

6.1.3 Results

The results obtained during these tests are contained in Figure 1 and Tables II through IV.

6.0 REQUIREMENTS, PROCEDURES AND RESULTS (Continued)

6.2 Time Constant Test

6.2.1 Requirements

The requirements of this test were to obtain the time constant for the collector at inlet temperature controlled to ambient air temperature with the solar flux level of 230 BTU/Hr·Ft^2, and liquid flow rate of 224.9 Lb/Hr. The following data were recorded for the test.

1.	Collector side wall temperature	(°F)
2.	Collector back side temperature	(°F)
3.	Collector outer cover temperature	(°F)
4.	Absorber surface temperature - North side	(°F)
5.	Absorber surface temperature - Center	(°F)
6.	Absorber surface temperature - West side	(°F)
7.	Absorber surface temperature - South side	(°F)
8.	Ambient temperature	(°F)
9.	Liquid inlet temperature	(°F)
10.	Liquid outlet temperature	(°F)
11.	Liquid differential temperature	(°F)
12.	Solar flux	(BTU/Hr·Ft^2)
13.	Flow rate	(Lb/Hr)
14.	Wind speed	(MPH)

6.2.2 Procedure

1. Establish required liquid flow rate.
2. Establish required inlet temperature.
3. Establish required solar flux level.
4. Establish required wind speed.
5. Record data for 5 minute stablized period.
6. Shut off solar simulator and maintain the inlet conditions.
7. Record the change of differential temperature on a strip chart recorder.

6.2.3 Results

The results obtained during these tests are contained in Figure 2 and Table V.

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6.0 REQUIREMENTS, PROCEDURES AND RESULTS (Continued)

6.3 Incident Angle Modifier Test

6.3.1 Requirements

The requirements of this test were to determine the effect of incident angle on the collector at inlet temperature controlled to ambient air temperature with a liquid flow rate of 224.9 Lb/Hr with the collector tilted at 45°, 60° and 75° with respect to the solar simulator surface. The following data were recorded for the test.

1.	Collector side wall temperature	(°F)
2.	Collector back side temperature	(°F)
3.	Collector outer cover temperature	(°F)
4.	Absorber surface temperature - North side	(°F)
5.	Absorber surface temperature - Center	(°F)
6.	Absorber surface temperature - West side	(°F)
7.	Absorber surface temperature - South side	(°F)
8.	Ambient temperature	(°F)
9.	Liquid inlet temperature	(°F)
10.	Liquid outlet temperature	(°F)
11.	Liquid differential temperature	(°F)
12.	Solar flux	($BTU/Hr \cdot Ft^2$)

6.3.2 Procedure

1. Set up collector at required tilt angle.

2. Establish required flow rate.

3. Establish required inlet temperature.

4. Establish solar simulator flux level.

5. Record the flux level on the collector surface.

6. Record data for 5 minute stablized period.

7. Repeat above steps as necessary to complete the required tests.

6.3.3 Results

The results obtained during the test are depicted in Figures 3 and 4, and Table VI.

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7.0 ANALYSIS

7.1 Thermal Performance Test

The analysis of data contained in this report is in accordance with the National Bureau of Standards recommended approach. This approach is outlined below.

The efficiency of a collector is stated as:

$$\eta = \frac{q_u/A}{I} = \frac{\dot{m}\, C_{tf}\,(t_{f,e} - t_{f,i})}{I} \qquad (1)$$

where:

q_u = rate of useful energy extracted from the Solar Collector (BTU/Hr)

A = Total collector area (ft^2) Ⓐ

I = Total solar energy incident upon the plane of the solar collector per unit time per unit area ($BTU/Hr \cdot Ft^2$)

$\dot{m}$ = Mass flow rate of the transfer liquid through the collector per unit area of the collector ($Lbm/Hr \cdot Ft^2$) Ⓐ

Ctf = Specific heat of the transfer liquid (BTU/Lb·°F)

$t_{f,e}$ = Temperature of the transfer liquid leaving the collector (°F)

$t_{f,i}$ = Temperature of the transfer liquid entering the collector (°F)

Rewriting Equation (1) in terms of the total collector area yield:

$$\eta = \frac{(\dot{m}A)C_{tf}\,(t_{f,e}-t_{f,i})}{(IA)} = \frac{\dot{M}\, C_{tf}\,(t_{f,e}-t_{f,i})}{P_i} \qquad (2)$$

Notice that:

P_i = IA = Total Power Incident on the Collector

$\dot{m}A = \dot{M}$ = Total Mass Flow Rate through the Collector

Therefore $\dot{M}\, C_{tf}\,(t_{f,e}-t_{f,i})$ = Total Power Collected by the Collector

7.0 ANALYSIS (Continued)

7.1 Thermal Performance Test (Continued)

Substitution in Equation (2) results in:

$$\eta = \frac{P_{abs}}{P_{inc}} \tag{3}$$

where:

P_{abs} = Total collected power

P_{inc} = Total incident power

This value of efficiency is expressed as a percentage by multiplying by 100. This expression for percent efficiency is:

$$\text{Collector Efficiency} = \frac{P_{abs}}{P_{inc}} \times 100 \tag{4}$$

or from Equation (2), collector efficiency is defined by the equation:

$$\%\ \text{Eff.} = \frac{\dot{M}\, C_{tf}\, (t_{f,e} - t_{f,i})}{P_i} \times 100 \tag{5}$$

Each term in Equation (5) was measured and recorded independently during the test. The calculated values of efficiency were determined at seventy-second intervals. The mean value of efficiency was determined over a five-minute period during which the test conditions remained in a quasi-steady state. Each five-minute period constitutes one "data point" as is graphically depicted on a plot of percent efficiency versus

$\left((t_{f,i} - t_a) \ / I \right)$

where:

$t_{f,i}$ = Liquid inlet temperature (°F)

t_a = Ambient temperature (°F)

I = Incident flux per unit area (BTU/Hr·Ft^2)

The abscissa term $\left((t_{f,i} - t_a) \ / I \right)$ was used to normalize the effect of operating at different values of I, $t_{f,i}$ and t_a. The results are found in Figure 1.

The result of second order polynomial analysis is shown in Figure 1. The first order polynomial to best describe the test results is:

$$\text{Efficiency} = a_0 + a_1 \mathcal{I}$$

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7.0 ANALYSIS (Continued)

7.1 Thermal Performance Test (Continued)

where:

$\mathcal{I}' = (t_{f,i} - t_a) / I$

and the coefficients are determined to be:

WIND	0 MPH	10 MPH	13 MPH
a_0	.775	.787	.743
a_1	-.568	-.687	-.575

7.0 ANALYSIS (Continued)

7.2 Time Constant Test

Two methods are proposed by ASHRAE 93-P for conducting a time constant test. However, due to facility limitations, only the first method could be used. This method consisted of shutting down the simulator and maintaining a constant flow rate and inlet temperature while obtaining data.

According to the definition of time constant given in 93-P, it is the time required for the ratio of the differential temperature at time τ to the initial differential temperature to reach .368. It can be expressed as:

$$\frac{T_{f,e\ \tau} - T_{f,i}}{T_{f,e,ini} - T_{f,i}} = .368 \qquad (1)$$

If the inlet liquid temperature can not be controlled to equal the ambient air temperature, then the following equation must be used

$$\frac{F_R U_L\ (t_{f,i} - t_a) + \frac{\dot{m}C_p}{A}\ (t_{f,e,\ \tau} - t_{f,i})}{F_R U_L\ (t_{f,i} - t_a) + \frac{\dot{m}C_p}{A}\ (t_{f,e,ini} - t_{f,i})} = .368 \qquad (2)$$

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where:

$T_{f,e,\tau}$	Exit liquid temperature at time τ (A)
$T_{f,i}$	Inlet liquid temperature
$T_{f,e,ini}$	Initial exit liquid temperature
$\dot{m}$	Liquid mass flow rate = 224.9 Lb/Hr
C_p	Specific heat of liquid = .78 BTU/Lb·°F
A	Collector area = 15.3 Ft^2
$F_R U_L$	Negative of the slope determined from the thermal efficiency curve

During the time constant test, the inlet liquid temperature can not be controlled to within ±2°F of ambient air temperature, hence equation (2) must be used for evaluation. From the performance curve, it is found that $F_R U_L$ = .68. Equation (2) becomes

$$\frac{.68\ (80.9-77.5) + 11.28\ \left(\frac{t_{f,e\tau} - 80.9}{15}\right)}{.68\ (80.9-77.5) + 11.28\ \left(\frac{\quad}{15}\right)} = .368$$

7.0 ANALYSIS (Continued)

7.2 Time Constant Test (Continued)

or

$$\frac{t_{f,e}\ \tau - t_{f,i}}{t_{f,e,ini} - t_{f,i}} = .360$$

From Figure 2 the time constant was determined to be 2 minutes and 24 seconds.

7.0 ANALYSIS (Continued)

7.3 Incident Angle Modifier Test

Two methods are proposed by ASHRAE 93-P for incident angle modifier tests. For the MSFC Solar Simulator Facility, only method 1, (tilting the collector) is applicable. The collector was adjusted so that the incident radiation angles were 45°, 60° and 75° to the normal of the collector surface.

According to 93-P, the incident angle modifier is defined as

$$K_{\alpha\tau} = \frac{\eta}{F_R(\tau\alpha)_n} \qquad (1)$$

where η = efficiency at tilted angle

$F_R(\alpha\tau)_n$ = Intercept of efficiency curve at normal incident angle = .78

For equation (1) to be applicable, the inlet liquid temperature must be controlled to within ± 2°F of the ambient air temperature. In cases where the inlet liquid temperature can not be controlled to within ± 2°F the following equation must be used to evaluate the incident angle modifier

$$K_{\alpha\tau} = \frac{\eta + F_F U_L \dfrac{T_{f,i} - T_a}{I}}{F_R(\alpha\tau)_n} \qquad (2)$$

where:

$F_R U_L$ is the negative of the slope determined from the thermal efficiency curve.

Table VI shows that the inlet liquid temperature were not all within ± 2°F of ambient air temperature. Hence, equation (2) was used for evaluation.

$$K_{\alpha\tau} = \frac{\eta + .68 \dfrac{T_{f,i} - T_a}{I}}{.78}$$

The results of this computation are shown on Table VI and plotted against incident angle in Figure 3 and plotted against $\frac{1}{\cos\theta_i} - 1$ in Figure 4.

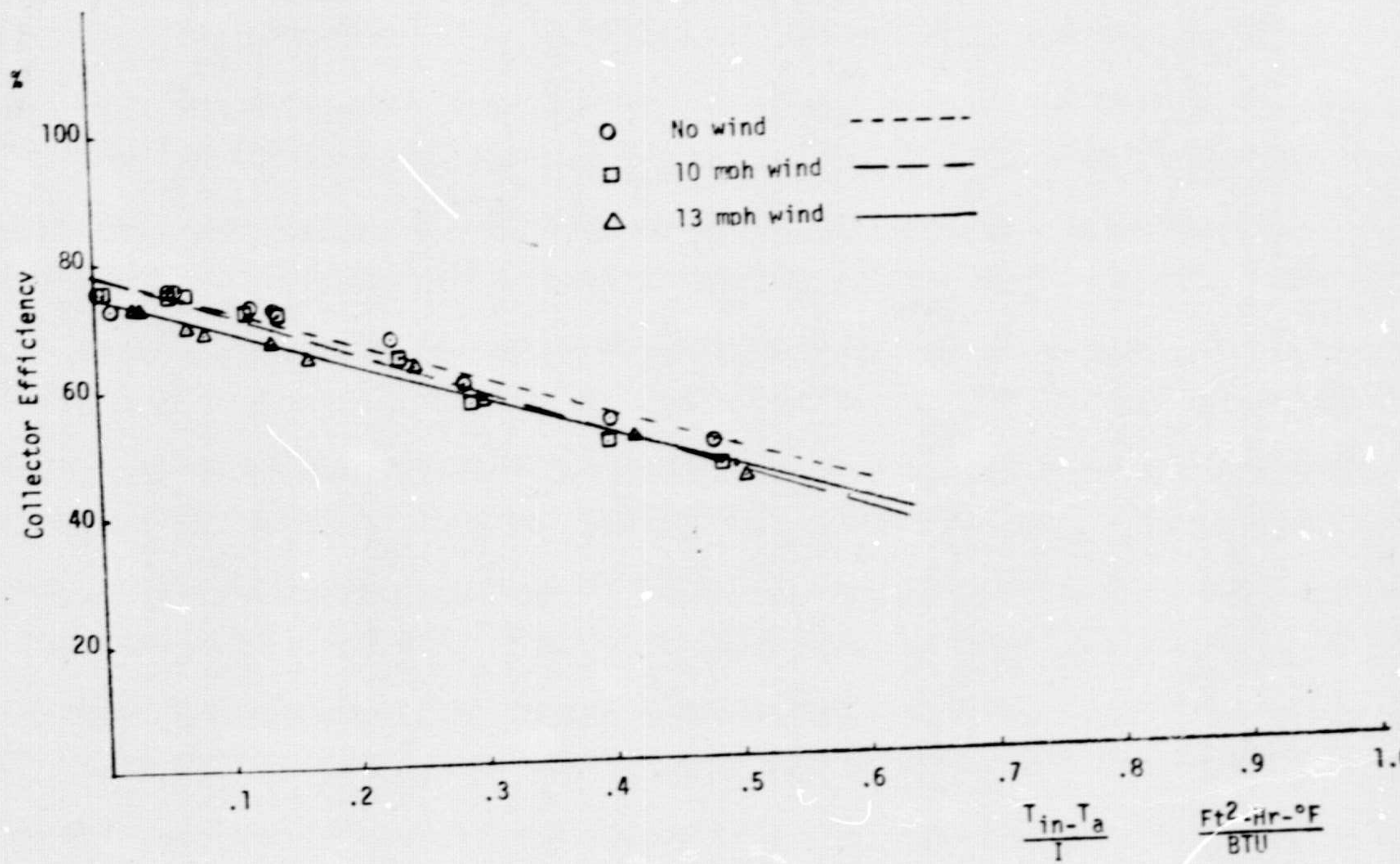


Figure 1. Lennox/Honeywell Collector Indoor Thermal Performance Test

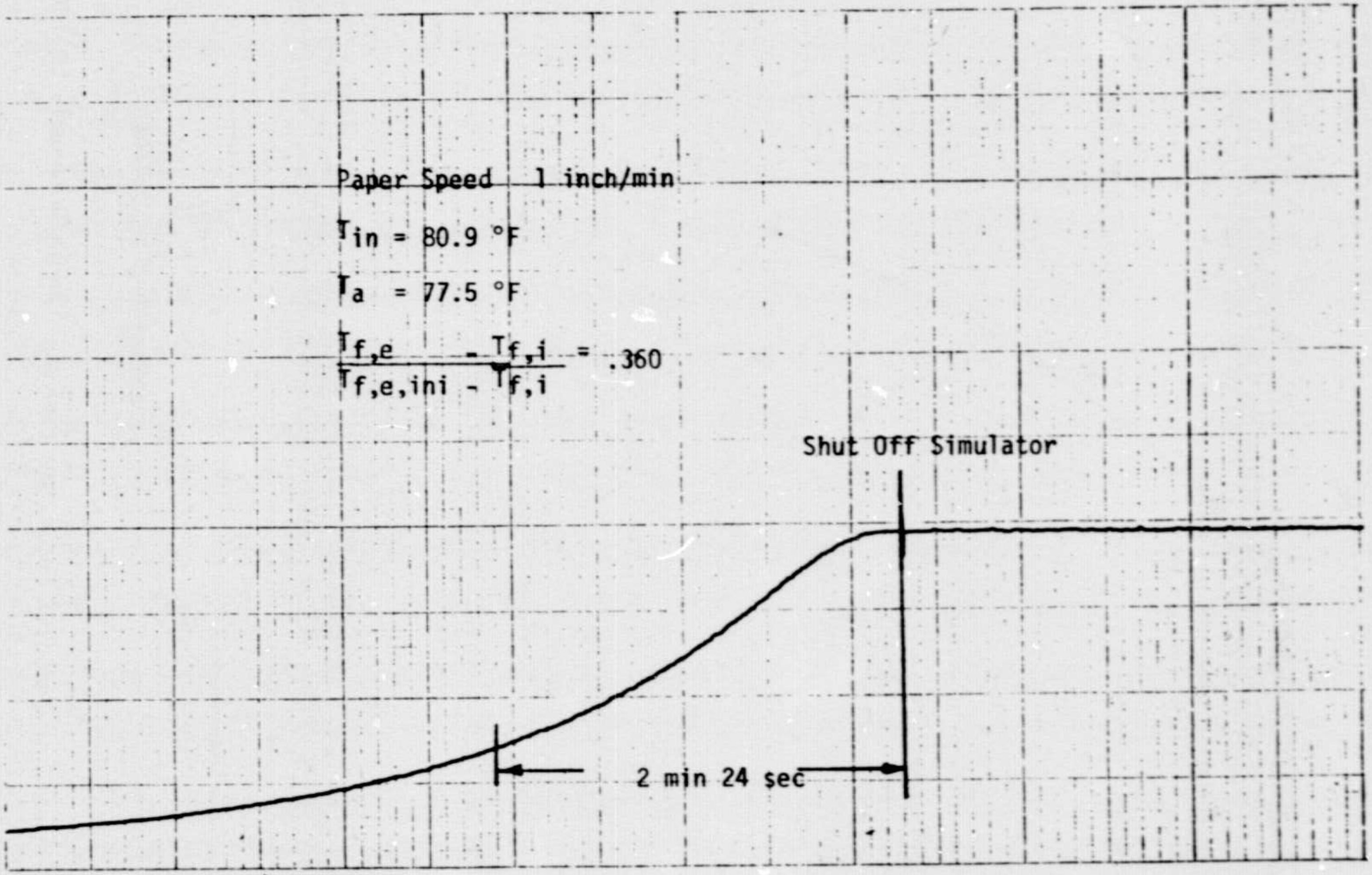


Figure 2. Lennox/Honeywell Collector Time Constant Test

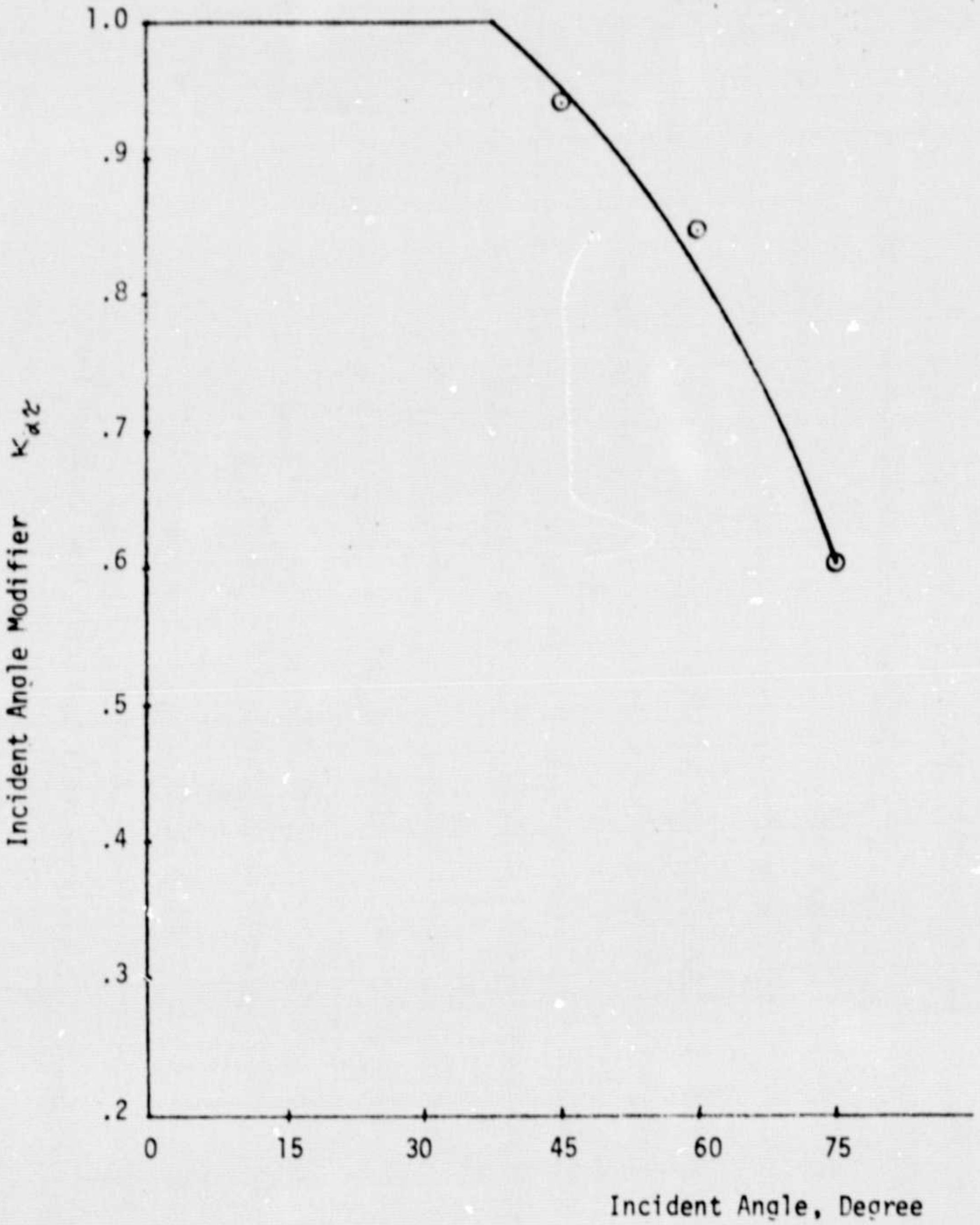


Figure 3. Incident Angle Modifier for Lennox/Honeywell Collector

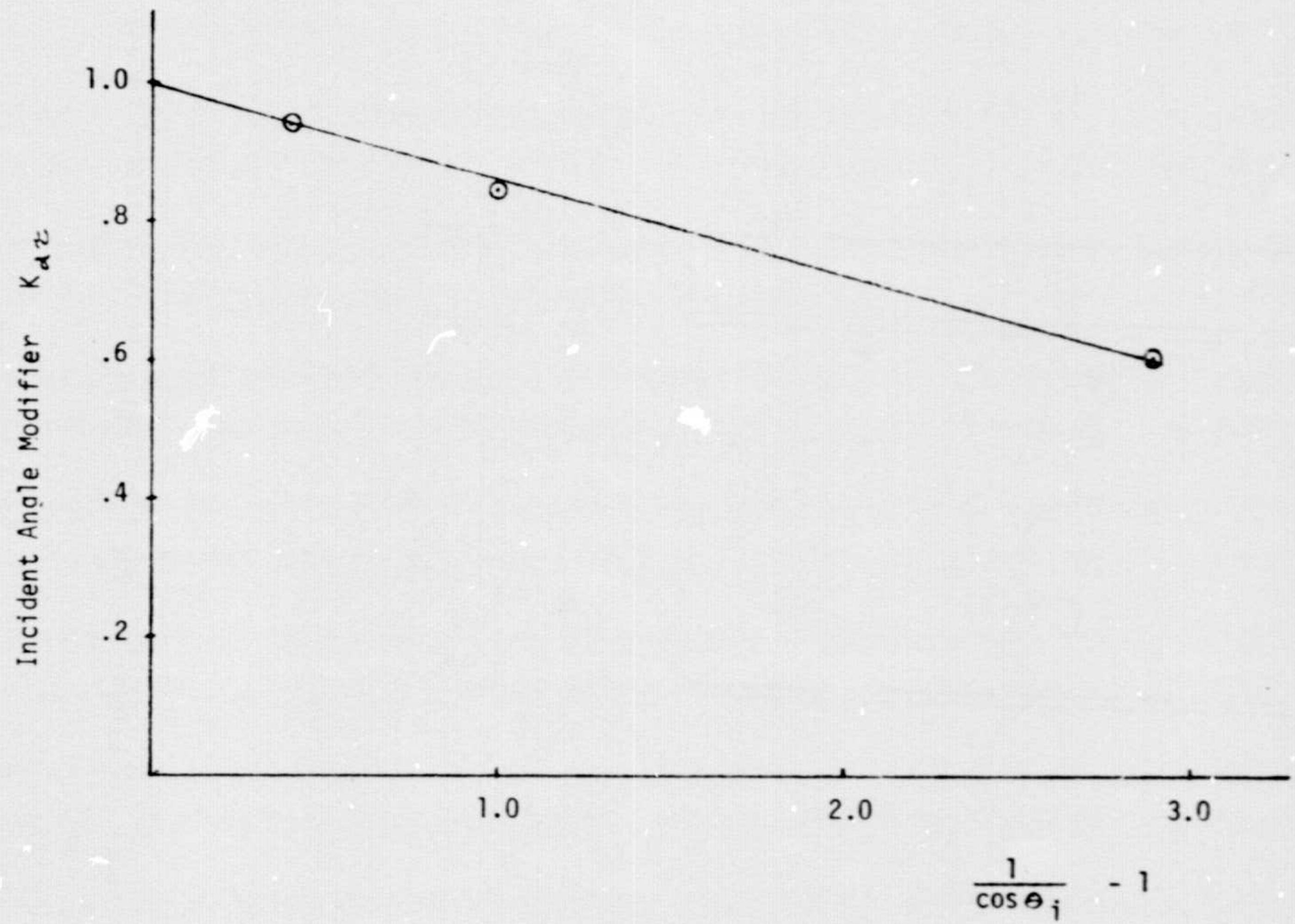
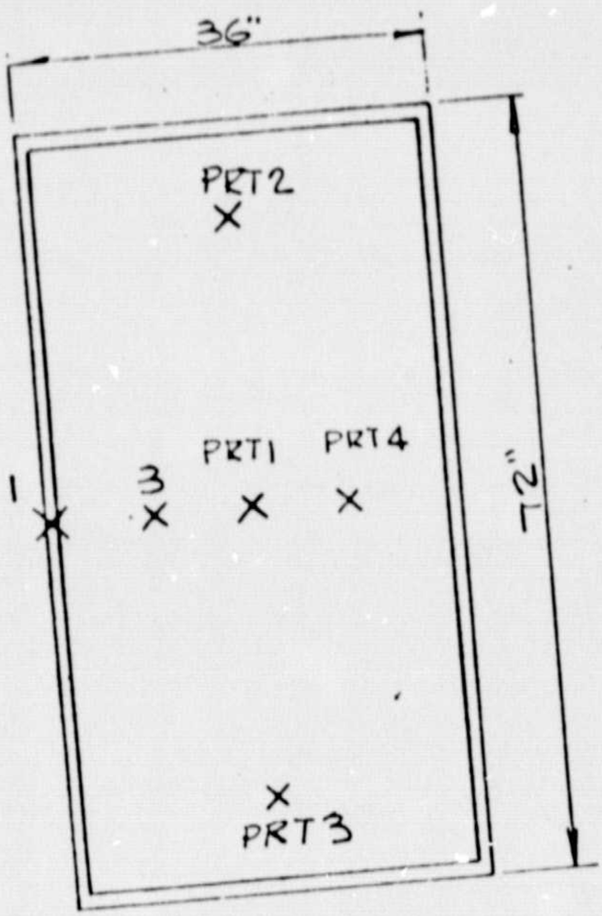


Figure 4. Incident Angle Modifier for Lennox/Honeywell Collector



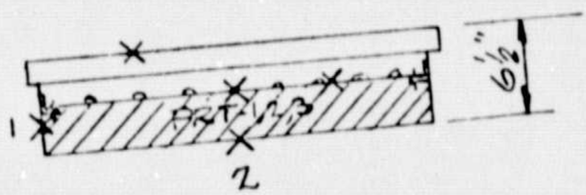


Figure 5. Lennox/Honeywell Collector Instrumentation Locations

TABLE I.

LENNOX/HONEYWELL COLLECTOR SIMULATOR TEST CONDITIONS

Solar Flux BTU/Hr·Ft^2	Inlet Temp. °F	Flow Rate Lb/Hr	Wind MPH
240, 290	Ambient 100, 120, 150, 200	224.9	0, 10, 13

TABLE II

LENNOX/HONEYWELL COLLECTOR THERMAL PERFORMANCE TEST DATA - NO WIND

Collector Side °F	107.8	105.4	116.9	116.3	118.8	120.0	114.8	121.9	122.1	121.4
Collector Back °F	81.4	76.5	84.4	86.1	88.1	89.5	85.8	89.5	93.2	95.5
Outer Cover °F	104.9	101.3	111.8	113.3	115.0	117.3	113.1	119.3	126.3	126.2
Surface - North °F	121.7	116.8	138.1	144.6	156.3	162.2	179.7	188.3	225.9	232.6
Surface - Center °F	116.9	112.7	133.2	139.0	151.4	156.6	175.7	183.7	222.1	228.2
Surface - East °F	116.5	112.4	132.7	138.4	150.4	155.6	174.2	182.0	219.2	225.0
Surface - South °F	109.8	106.0	126.9	132.1	145.9	150.6	171.5	178.2	218.6	223.7
Ambient °F	80.5	77.4	82.5	82.5	83.6	83.3	79.5	80.6	80.8	80.6
T_{in} °F	81.6	80.3	99.4	99.7	119.6	119.5	149.6	149.2	200.0	199.6
T_{out} °F	98.5	95.1	115.7	118.9	135.0	137.6	161.5	165.4	209.5	212.1
ΔT °F	16.8	14.8	16.3	19.2	15.4	18.1	11.9	16.2	9.5	12.5
Flow Rate Lb/Hr	225.6	228.7	224.9	224.5	223.6	224.0	225.5	225.6	225.6	226.5
Flux BTU/Hr·Ft2	255.4	240.0	255.0	297.9	255.0	297.6	243.6	297.0	243.6	297.0
Efficiency %	75.6	72.1	75.3	75.6	72.0	72.6	59.6	67.0	49.3	53.5
$(T_i - T_a)/I$ °F·Hr·Ft^2/BTU	.004	.012	.066	.058	.141	.122	.288	.231	.483	.401

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TABLE III

LENNOX/HONEYWELL COLLECTOR THERMAL PERFORMANCE TEST DATA - 10 MPH WIND

Collector Side °F	97.5	100.1	99.5	101.4	101.5	94.3	101.6	101.0	100.6
Collector Back °F	80.2	85.2	86.9	88.9	90.2	87.6	90.2	94.4	94.4
Outer Cover °F	91.0	94.0	95.0	95.8	97.2	92.0	96.7	98.1	98.7
Surface - North °F	121.4	138.0	144.3	156.0	161.7	179.0	188.0	224.6	231.5
Surface - Center °F	116.6	133.2	138.9	151.2	156.3	175.1	183.0	220.8	227.2
Surface - East °F	116.3	132.5	137.9	150.0	154.9	172.9	181.1	217.4	223.6
Surface - South °F	109.5	126.8	131.8	145.6	150.1	170.8	177.6	217.2	222.8
Ambient °F	79.7	81.4	82.4	83.0	84.4	78.7	79.5	80.7	80.9
T_{in} °F	81.3	99.5	99.7	119.5	119.4	149.7	149.6	199.6	199.8
T_{out} °F	98.1	115.7	118.7	134.6	137.3	161.1	165.1	208.6	211.5
ΔT °F	16.8	16.2	19.0	15.1	17.9	11.4	15.5	9.0	11.7
Flow Rate Lb/Hr	224.8	225.1	224.3	225.6	223.5	224.2	224.3	226.1	224.4
Flux BTU/Hr·Ft^2	255.4	255.0	297.9	255.0	297.6	243.6	297.0	243.6	283.0
Efficiency %	75.1	74.8	74.7	71.3	71.7	56.7	63.7	45.7	50.4
$(T_i - T_a)/I$ °F·Hr·Ft^2/BTU	.006	.071	.058	.143	.118	.291	.236	.488	.420

TABLE IV

LENNOX/HONEYWELL COLLECTOR THERMAL PERFORMANCE TEST DATA - 13 MPH WIND

Collector Side	°F	92.2	93.4	95.1	97.1	97.5	100.7	96.4	101.2	102.2	104.9
Collector Back	°F	73.1	74.0	81.7	82.1	85.1	85.5	85.4	87.0	92.4	93.3
Outer Cover	°F	83.6	85.5	89.1	90.3	90.7	93.0	92.3	95.5	98.0	99.3
Surface - North	°F	117.3	125.2	133.9	141.5	152.3	160.0	178.4	186.5	224.8	231.4
Surface - Center	°F	113.2	120.5	130.0	136.8	148.4	155.4	174.7	182.0	221.3	227.3
Surface - East	°F	112.6	119.5	128.8	135.5	146.6	153.6	172.2	179.6	217.3	223.4
Surface - South	°F	106.5	112.7	124.1	130.1	143.2	149.4	170.3	176.7	217.7	222.9
Ambient	°F	72.0	72.5	78.3	78.3	79.4	79.8	78.6	79.4	81.2	81.5
T_{in}	°F	80.6	81.0	99.2	99.3	119.8	120.0	149.7	150.0	200.6	200.3
T_{out}	°F	95.7	99.5	113.3	116.7	132.7	136.3	160.7	164.5	208.9	211.6
ΔT	°F	15.1	18.5	14.1	17.4	12.9	16.3	11.0	14.5	8.3	11.3
Flow Rate	Lb/Hr	225.4	224.6	225.2	224.2	225.4	224.9	225.5	225.1	224.1	224.7
Flux	$BTU/Hr \cdot Ft^2$	240.0	293.0	242.6	293.0	242.0	293.0	236.0	283.0	237.0	283.0
Efficiency	%	72.5	72.4	68.2	69.6	64.0	66.8	56.9	62.7	43.9	50.4
$(T_i - T_a)/I$	$°F \cdot Hr \cdot Ft_2/BTU$	.036	.030	.086	.072	.167	.137	.301	.250	.508	.42

TABLE V

LENNOX/HONEYWELL COLLECTOR TIME CONSTANT TEST DATA

Time	14:11:30	14:12:55	14:14:20	14:15:45	14:17:11	14:18:36	14:20:01	14:21:26	14:22:51
Collector Side °F	93.5	93.7	93.7	93.4	93.6	92.9	91.0	89.4	87.6
Collector Back °F	79.2	79.2	79.3	79.3	79.4	79.4	79.5	79.5	79.5
Outer Cover °F	87.4	87.5	87.5	87.6	87.7	87.6	83.2	82.1	81.5
Surface - North °F	116.0	116.1	116.3	116.5	116.6	106.6	94.4	88.4	85.5
Surface - Center °F	112.1	112.3	112.4	112.6	112.7	103.2	91.1	85.8	83.4
Surface - East °F	111.6	111.7	111.9	112.0	112.2	97.5	88.7	84.7	82.7
Surface - South °F	105.3	105.6	105.7	105.8	106.0	91.2	84.1	81.9	81.2
Ambient °F	77.4	77.7	77.5	77.5	77.7	77.9	77.5	77.2	77.4
T_{in} °F	80.0	80.1	80.3	80.5	80.7	80.8	80.9	81.0	81.0
T_{out} °F	95.0	95.1	95.3	95.5	95.7	92.0	86.3	83.9	82.8
ΔT °F	15.0	15.0	15.0	15.0	15.0	11.2	5.4	2.9	1.8
Flow Rate Lb/Hr	224.3	223.6	223.1	223.1	222.5	222.3	221.6	220.9	220.5
Flux BTU/Hr·Ft^2	237	237	237	237	237	0	0	0	0
Wind MPH	13	13	13	13	13	13	13	13	13

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TABLE VI

LENNOX/HONEYWELL COLLECTOR INCIDENT ANGLE MODIFIER TEST DATA

Incident Angle	45	60	75
Surface - North °F	108.6	99.8	89.2
Surface - Center °F	105.2	96.6	86.9
Surface - East °F	103.0	91.0	84.5
Surface - South °F	99.6	91.8	84.9
Ambient °F	69.8	71.0	81.0
T_{in} °F	82.0	81.2	80.7
T_{out} °F	92.8	88.6	84.2
ΔT °F	10.8	7.4	3.5
Flow Rate Lb/Hr	225.2	226.3	230.1
Flux BTU/Hr·Ft^2	179.8	138.6	87.4
Efficiency %	68.7	61.1	47.1
$K_{\alpha\tau}$	.940	.847	.604

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